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Numerical analysis for microstructure control in hot forming process

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Abstract

The importance of structural metals for industrial applications is based on their superior combination of mechanical properties - strength, elongation, toughness and corrosion resistance – achieved at the end of forming processes. A numerical analysis for the prediction of microstructure is strongly required for the optimization of hot forming process parameters, because the microstructure of structural metals, which has the significant effects on mechanical properties, is strongly dependent to forming process conditions as well as the chemical composition. The off-line and on-line analyses of microstructure evolution are explained briefly, and the results of its application to hot strip rolling are presented. The linkage of microstructure analysis to kinetic property prediction of product is discussed, and finally, the remaining research topic, such as enlarging the analytical scheme to various alloys, is presented.

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Keywords: Forming; Microstructure; Analytical Scheme

1. Introduction

The most important demand for structural metals is that for good mechanical properties such as high strength, elongation, toughness and corrosion resistance. These properties are governed by the microstructure of formed product. Thus, the optimization of the forming conditions or forming process parameters, referring to the microstructure of the formed product for the target values, is gaining increasing importance in the research and development of hot forming technologies. The above optimization of forming condition has two aspects of hardware and software technologies. The first one, hardware technologies, such as controlled rolling process, high

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reduction rolling mill, controlled and rapid cooling system and coiling system, has marked significant progress in the past decades, as has been reviewed by Ouchi (2001). The major achievement of the software technologies is micro-alloying technologies used to control the change of the microstructure of hot metal being formed, as was reviewed by Ouchi (2001) and Tamura (1987).

The hardware and software technologies should be considered together, even though their individual optimal orientations within industrial applications are mutually opposing. This necessitates the numerical analysis for predicting the microstructure and kinetic properties of structural metal after hot/cold forming in order to satisfy both requirements as described by Yanagimoto (2008). The aim of this paper is to point out the current status and remaining problems to realize the microstructure and kinetic properties predictions for a wide range of structural metals by forming.

2. Analytical method of microstructural evolution and plastic deformation in hot forming

The analytical method of microstructural evolution is categorized into two groups. The first is the microstructure analysis scheme. It contains the evolutional equation for the analysis of grain structure, which is governed by metallurgical phenomena, such as work hardening, recovery and recrystallization of the material, caused by the transient change in the temperature and the strain rate of every material point. This scheme involves the use of the kinetics of microstructural evolution, which is called the material genome by Yanagimoto (2001), as the boundary conditions in the analysis. The 'analytical scheme used as the evolutional equation' and 'the kinetics used as the material genome' were not always distinguished in the past. The second group is the deformation analysis as FEM.

2.1. Analytical scheme for the evolution of microstructure

Sellars and Whiteman (1979) and Laasraoui and Jonas (1991) carried out consistent investigations on microstructural evolution during the hot forming of steels, and the results of the experiments have been summarized as empirical models. Those empirical models have been used for the prediction of the industrial hot rolling process by Beynon and Sellars (1992). In their analysis, the 'analytical scheme used as the evolutional equation' and 'the kinetics used as the material genome' were not always distinguished, so that the transient change in temperature and strain rate cannot be reflected in the microstructural change.

Yada et al. (1983) and Senuma et al. (1984a) extensively investigated the measurement of the microstructural evolution of C-Si-Mn steels during hot compression, and they found equations on the kinetics of, for example, work hardening, dynamic and static recoveries, dynamic and static recrystallization and grain growth as functions of process variables such as temperature, strain rate and strain. They proposed an analytical model to predict the flow stress and microstructural evolution, taking dislocation density as a representative variable. Senuma et al. (1984b) also tried to express their model by the differential description aimed at estimating the microstructural evolution and flow stress after transient changes in process variables such as temperature and strain rate. However, their effort was not a total success, because of the insufficiency of numerical solution of their differential form.

Finite element analysis of the metal forming process propagated in the 1980s. As the FEM can reveal the transient changes in temperature and strain rate at each point of the structural metal during forming, we need a new approach to reflect this transient change in process variables in the evolution of microstructure. This movement promoted the development of an evolutional method by Karhausen and Kopp (1992) and an incremental dislocation density and microstructural evolution analysis method by Yanagimoto et al. (1998). This formulation was extended to static events by Yanagimoto and Liu (1999), and to phase transformation by Liu and Yanagimoto (2001).

2.2. Deformation analysis

Metal forming has two major functions: the first is the generation of product geometry, and the second is the generation of mechanical properties. The generation of product geometry is realized by designing the die profile and forming conditions for the material to be formed, and the deformation analysis of the material being formed is of primary importance. In the last decade of the 20th century, finite element analyses of metal forming processes began to be used in practice, as was demonstrated by Mori and Osakada (1982). The computer aided engineering (CAE) system for the metal forming process is now widely used in metal forming industries. With this system, the three-dimensional distribution of strain rate and temperature can be analyzed, and their transient changes can be known, even that inside the material. Then, the challenging target for these CAE systems is to simulate the evolution of the microstructure of the metal, because the microstructure generated during hot forming has significant effects on the mechanical properties of the product.

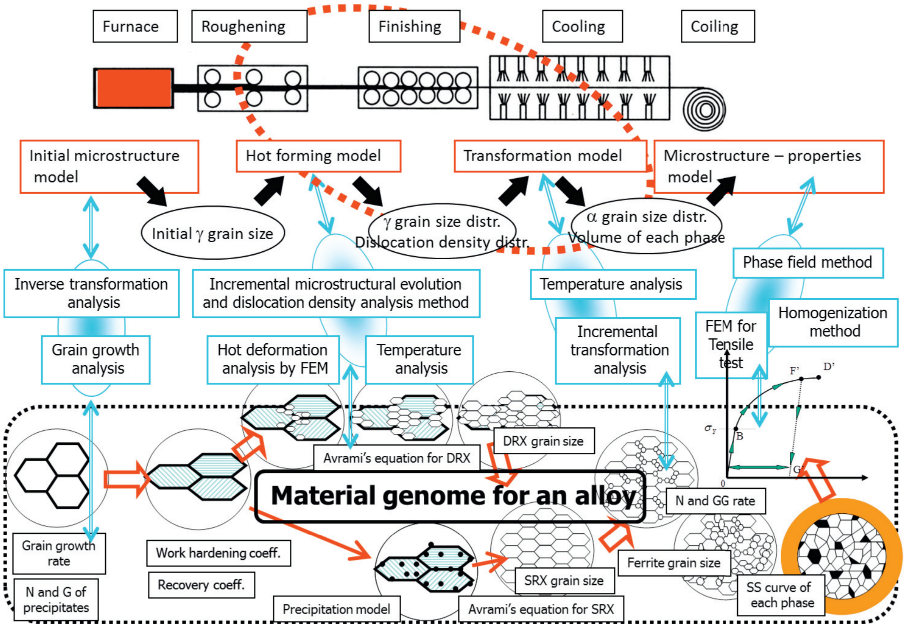

Fig. 1. Integrated model for the evolution of microstructure in hot forming.

2.3. Microstructure analysis during hot forming induced by plastic deformation

The general construction of the analytical scheme is illustrated in Fig. 1, taking the hot strip rolling of steel sheet as an example. The whole analytical scheme for the analysis of the microstructural evolution is divided into several components: initial microstructure model, hot forming model, transformation model and microstructure-property model. The microstructure-property model is still the focus of many basic investigations, but no general approach is available. The hot forming model and transformation model are coupled with the three-dimensional finite element analysis of various rolling processes. Fig. 2 shows the results of applying microstructural analysis to the strip rolling process to assess the effect of the thickness reduction balance of the finishing train of a 6-stands hot strip mill on the final microstructure after transformation, as obtained by Morimoto et al. (2007). The incremental dislocation density and microstructural evolution analysis method are used to estimate the dislocation density and microstructure in forming. Temperature at the finishing stand is 850°C and thickness reductions are 48%-42%-37%-36%-29% and 20% in the conventional schedule A. In the new schedule B, the exit temperature is 750 °C and thickness reductions are 38%-37%-32%-40%-41% and 38%. Larger thickness reductions at latter stands in the finishing train yield steel strips with finer grains. The analytical results agree well with the experimental measurements.

3. Requirements for kinetic property prediction and materials genome

In the on-line model for the optimization and control of hot strip mill, the kinetic property prediction of rolled strip is implemented, as presented by Agarwal and Shivpuri (2012) and Ohara et al. (2014). There are empirical equations presented and summarized by Pickering (1978), and such kinetic property model is enough to predict kinetic properties, taking variables obtained by present microstructure analysis model as input parameters, because on-line prediction of microstructure is mainly conducted for the steels with high amount of production such as C-Si-Mn steels or low micro-alloyed steels.

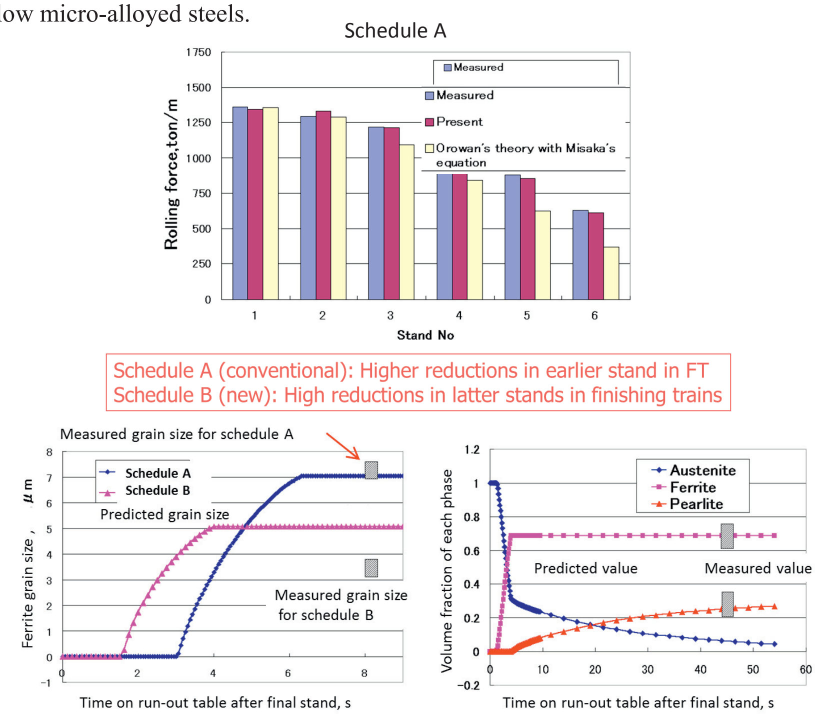

Fig. 2. Rolling force, ferrite grain size and volume fraction of each phase after rolling.

However, in the off-line analysis of microstructure, the microstructure-property model is not yet fully realized, due to higher requirements for the accuracy and more complex microstructures. The defects of stamping depend on the kinetic properties of the sheet metal as shown in Fig. 3. The kinetic properties are strongly dependent on the structure of the metal. The model should consider the effect of the complex morphologies of modern steels, for example the high strength steels, to accurate predict the kinetic properties such as the stress-strain curves, which could be used as the input data for the stamping analysis. In order to characterize the kinetic properties change as a function of microstructure and morphologies, numerous experiments and analytical scheme might be needed.

Furthermore, the material genome, that is, the empirical equation to describe, for example, work hardening, recovery and recrystallization as functions of strain rate, strain and temperature for each alloy composition, are missing in most of the structural steels. As numerous commercial structural metals are used, we require a large number of experiments to obtain the material genome. Such material genome is revealed in Cr-Mo-V steels and stainless steels as shown in Table 1, but we should continue laborious experiments to decode the genome.

It can be emphasized that innovative numerical methods of describing 1) the microstructure-mechanical property relationship, and 2) the kinetics of the change in microstructure as functions of strain rate and temperature, will be strongly required in the near future. These methods should enable the prediction of the above values for the complicated and diversified composition of microstructures, which are dependent on the chemical composition of the numerous commercial alloys.

4. Conclusion

The numerical analysis of microstructure after the hot forming of structural metals was explained in this paper.

Defects of formed sheet		Kinetic properties of material					
		Yield stress, YP	Tensile strength, TS	Total elongation	n-value (uniform elongation)	r-value	Young's modulus
Fracture (α: less strength; β: less enlogation)	α-fracture (deep drawing)	-	-	-	**	***	-
	α-fracture (stretching)	-	*	***	**	*	-
	β-fracture	-	*	**	*	**	-
	Fracture in bending	-	*	**	*	-	-
Surface	Wrinkles in flange	***	*	-	*	**	-
	Wrinkles in body	***	*	-	**	**	-
	Surface strain	***	*	-	**	*	*
	Others	**	*	-	**		**
Geometry		***	*	-	**	- or *	*

Fig. 3. Effects of kinetic properties to the defects in sheet forming. Press forming handbook (1997), eds. Sheet Forming Committee, Nikkan Kogyo Press (in Japanese). Amplitude of influence is classified by number of asterisk.

Table 1. Material genome for C-Si-Mn steel, Cr-Mo-V steel and type 316 stainless steel (Soltanpour et al., 2012; Dupin, et al., 2014).

	Parameter	Plain C-Si-Mn Steel	Cr-Mo-V steel	316 Stainless Steel
	Initial grain size, d_0	63 μm	120 μm	55 μm
	Activation energy, Q_{DRX}	266 kJ/mol	433 kJ/mol	368 kJ/mol
	Work hardening coef., c	1.08 x10^{13}	2.17 x10^{11}	2.87 x10^{11}
	Dynamic recovery coef. , b	$9850\left[\dot{\varepsilon}^{0.685}\exp\left(\frac{-8000}{T}\right)\right]$	$1.54\times10^{6}\left[\dot{\varepsilon}^{0.49}\exp\left(\frac{-14200}{T}\right)\right]$	$11820\left[\dot{\varepsilon}^{0.67}\exp\left(\frac{-10864}{T}\right)\right]$
	Critical strain, ε_c	$4.76\times10^{-4}\left[\exp\left(\frac{8000}{T}\right)\right]$	$0.08\left[\dot{\varepsilon}\exp\left(\frac{38800}{T}\right)\right]^{0.054}$	$0.019\left[\dot{\varepsilon}\exp\left(\frac{44900}{T}\right)\right]^{0.09}$
DRX	Rate of DRX, G	$\frac{0.693}{\left(7.63\times10^{-5}\left[\dot{\varepsilon}^{0.05}\exp\left(\frac{6420}{T}\right)\right]\right)^{2}}$	$9.24\times10^{4}\left[\dot{\varepsilon}^{-0.5}\exp\left(\frac{-15000}{T}\right)\right]$	$191252\left[\dot{\varepsilon}^{-0.31}\exp\left(\frac{-15747}{T}\right)\right]$
DRX	Volume Fraction, X_{DRX}	$1-\exp(-G(\varepsilon-\varepsilon_c)^2)$	$1-\exp(-G(\varepsilon-\varepsilon_c)^2)$	$1-\exp(-G(\varepsilon-\varepsilon_c)^2)$
DRX	Grain size, d_{DRX}	$22600\left[\dot{\varepsilon}^{-0.27}\exp\left(\frac{-32000}{T}\right)\right]^{0.27}$	$1683\left[\dot{\varepsilon}^{0.15}\exp\left(\frac{-7500}{T}\right)\right]$	$27000\left[\dot{\varepsilon}^{-0.2}\exp\left(\frac{-13000}{T}\right)\right]$
SRX	Time 50% SRX, $t_{0.5}$	$2.3\times10^{-9}\left[\dot{\varepsilon}^{-0.2}\exp\left(\frac{150000}{RT}\right)\right]$	$1.04\times10^{-13}\left[\dot{\varepsilon}^{-1.04}\exp\left(\frac{318000}{RT}\right)\right]$	$8.4\times10^{-9}\left[\dot{\varepsilon}^{-0.4}\exp\left(\frac{219000}{RT}\right)\right]$
SRX	Volume Fraction, X_{SRX}	$1-\exp\left(-0.693\left(\frac{t}{t_{0.5}}\right)^{2}\right)$	$1-\exp\left(-0.693\left(\frac{t}{t_{0.5}}\right)^{1.31}\right)$	$1-\exp\left(-0.693\left(\frac{t}{t_{0.5}}\right)^{0.87}\right)$
SRX	Grain size, d_{SRX}	$5\Big/\left[\left(\frac{24}{\pi d_0}(0.491e^{\varepsilon}+0.155e^{-\varepsilon}+0.143e^{-3\varepsilon})\right)\right]^{0.6}$	$254\left[\varepsilon^{-0.67}\exp\left(\frac{-3920}{T}\right)\right]$	$265\left[\dot{\varepsilon}^{0.4}\exp\left(\frac{-4100}{T}\right)\right]$

Because of the difficulties and complexity of the numerical scheme, the practical application of a consistent model to industrial processes is not always promoted, particularly by forming scientists and engineers. There are two major drawbacks that must be solved: the lack of the material genome or functions for the kinetics of recovery and recrystallization, and the microstructure-mechanical properties relationships for an alloy being formed, as illustrated in Fig. 4. Resolving these issues will open a new era of manufacturing science, where the simultaneous design and optimization to produce products with high performance will be realized for all structural metals used in social activities.

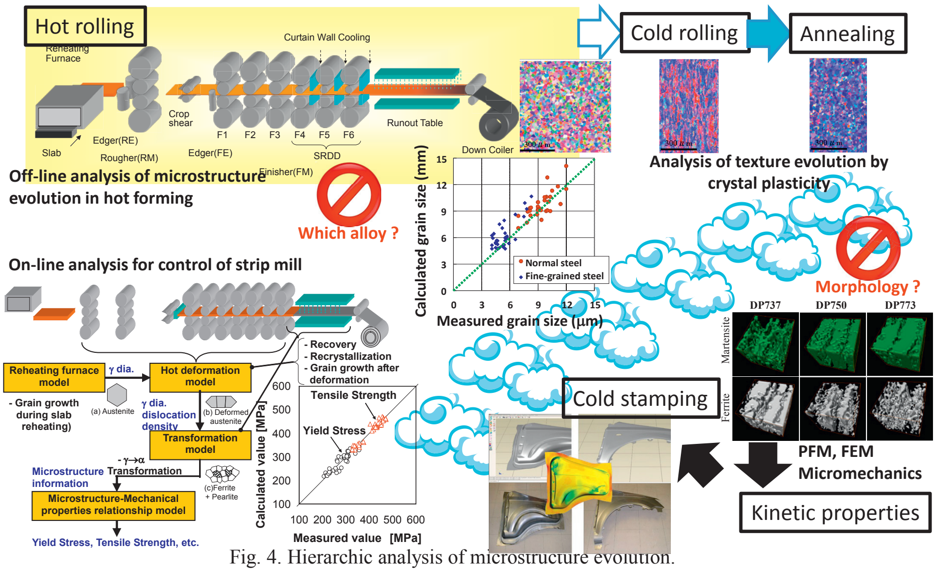

Fig. 4. Hierarchic analysis of microstructure evolution.

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